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WIREGRID PROGRAM FOR ANTENNA MODELLING INCLUDING SINUSOIDAL INT--ETC(U)
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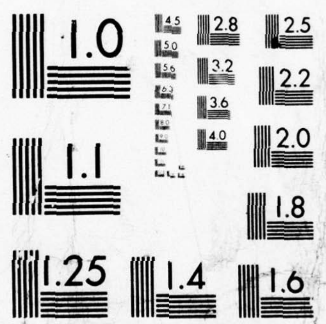
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(6) WIREGRID PROGRAM FOR ANTENNA MODELLING INCLUDING SINUSOIDAL INTERPOLATION OF CURRENT,

by

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Abstract

This report describes a method for computer modelling of aerial systems, especially aerials mounted on vehicles. It is based on the wiregrid modelling technique and uses a variation known as sinusoidal interpolation to represent the current in the wires of the model. Results are included for some preliminary test runs of the program, comparing them with standard results and the output of other modelling programs.

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FIGURES

1. INTRODUCTION

The analysis of the electromagnetic properties of an aerial system be it a single aerial, a combination of antennae or either in conjunction with a vehicle of some description, is both complex and time consuming. There exist many methods from which the characteristics can be determined, from the practical approach through to the rigorous analytical techniques, all of which have their limitations. The use of digital computers in this area for analysis and modelling has grown rapidly and many of the approximate methods depend extensively on them. If satisfactory techniques can be developed making use of high speed computing this will provide a valuable tool in the design of aerials and also the vehicles upon which they are mounted. They will also provide a useful insight into the mode of operation of an aerial and the interaction between it and other aerials or its mount. For example the skin currents of the vehicle carrying an aerial or the field radiated by different parts of the configuration could be calculated.

A computer program called WIREGRID has been developed to analyse some of the aspects of antenna performance using the wiregrid modelling method. In this method a linear conductor is represented by a line of wire elements and a conducting surface by a grid of wires along which current is constrained to flow. The aerial and its mount can, in this way, be represented by a series of discrete thin wire segments carrying current and giving rise to electric fields which interact to produce the electromagnetic characteristics of the antenna assembly. The main problem involved in this method is the determination of the currents carried by each wire element. This is tackled using Pocklingtons integral equation for the electric field of a thin wire and combining this with the boundary condition that the tangential electric field at the surface of a conducting body is zero. By considering each element in turn and the field produced at its centre (its matchpoint) by each other element and using the boundary condition, a set of simultaneous equations can be built up in terms of the current on each element and solved to yield the current distribution on the antenna and vehicle; from this current distribution the polar pattern and input impedance can be calculated.

Within the field of wiregrid modelling there are many variations in the choice of expansion functions for the current, interpolation schemes, junction treatments and testing functions, and the WIREGRID program contains one of the simplest approaches to the expansion of the current in the single conductor. This is to assume that there is constant current along the length of each element, which is called a "pulse current" basis function, and to consider each element as if it were disjointed from any attached to it with no attempt to conform to Kirchoffs Law at any element junction. This gives rise to large current discontinuities where elements meet and this affects the resulting field characteristics; the near field to a greater extent than the farfield. Another limitation to the program is that the field at the surface of each wire is only set to zero at one position (ie the testing function is a delta function). This approach is known as the Collocation method. (A discontinuity in current also occurs at the junctions, if the wire diameter is not constant, but this is not further discussed in the present paper).

When using the WIREGRID program it has been found, by comparing the farfield patterns produced by this with other methods, that at least eight elements are required for every wavelength of wire. Since computer time for the

program depends on a power varying between the square and cube of the number of elements, this means that for a vehicle of length 30 ft. the frequency range in which WIREGRID can be used is only up to 50 MHz. This is very limiting when the program is to be used for vehicles with aerials covering the whole of the VHF band, and in order to overcome this and improve the method, the program has been rewritten. This new program uses what is known as Sinusoidal Interpolation (1), which firstly represents the current on each element as a three term sinusoidal basis function which allows the current to vary along the length of the element. It also takes into account Kirchoffs Law, though not exactly, at the wire junctions. This is done in order to decrease the current discontinuities and more accurately model the current distribution on the surface.

In this report the method using sinusoidal interpolation is explained and some preliminary results discussed. Also in the appendices is an outline of each of the procedures used in the program except the one used for solving the set of simultaneous equations produced by the method, which remains virtually unchanged from the original. Otherwise new procedures have had to be written for matrix fill, calculation of current coefficients and farfield polar pattern determinations using the three term current basis.

1.1 Wiregrid Modelling Theory

The antenna system to be modelled is represented by a series of wire elements with currents flowing in them which generate electromagnetic fields. Each element may only be connected at its ends. All the elements have a matchpoint on their axes and halfway along their lengths, and it is at this point that the boundary condition is enforced.

The tangential electric field at any matchpoint is found by summing the electric fields produced by the unknown current elements, including the field due to its own current, at that point. In order to satisfy the boundary condition that the total tangential electric field is zero, this electric field can be set equal and opposite to the field produced at that point by the elements with known currents which drive the system. In this way a set of N linear equations can be built up of the form:-

$$\sum_{j=1}^{N} x_{ij} I_j = -E_i \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

where x_{ij} is the tangential field component at matchpoint i due to the unit current on element j,

I_j is the current flowing in the jth element,

N is the total number of unknown current elements,

and E_i is the tangential field at matchpoint i due to known current elements. These equations can be written in the following matrix form:-

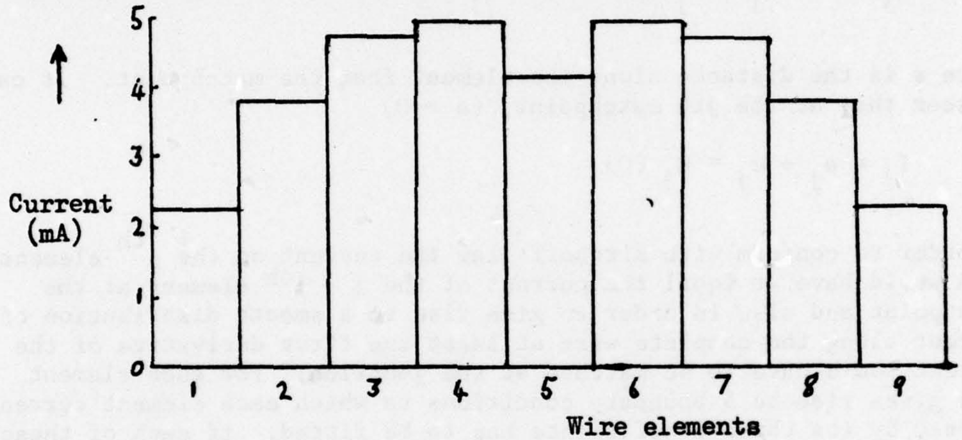
$$Z\,I = -E \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

where Z is called the mutual impedance matrix and is made up of the values of x_{ij}.

In the original WIREGRID program, as has been assumed above, the driven elements were specified with known currents. This is only one of many ways of describing the excitation of the system. Another possible excitation is to specify the voltage across the driven element. This is the method chosen for the new program. In the above equations N is now the total number of elements and E is zero at all matchpoints except for those in the driven elements where it equals the electric fields provided by the driving voltage. In this way the current distribution on the source is unknown and is found along with the currents in the non-driving elements, so that the input impedance can easily be found by dividing the voltage across the drive element by the current which has been calculated for it.

2. SINUSOIDAL INTERPOLATION

In the original WIREGRID program the current on the wires was taken to be uniform along the length of each element of that wire. The values of these currents were found by assuming adjacent elements were not connected together.



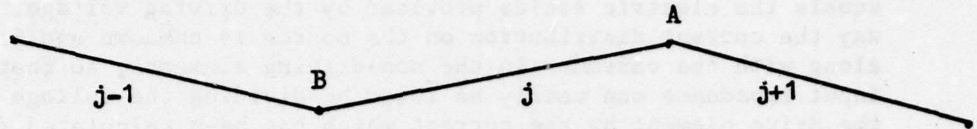
The diagram above shows the current distribution on a dipole of 9 elements analysed by the WIREGRID program, the current discontinuities are large at the element ends giving rise to large spikes in the near field of the dipole because of the charge build up at these points. A treatment of the problem is required that smooths the current distribution over the whole wire, minimising the current discontinuities. Another point to note is that the current does not go to zero at the ends of the dipole presenting an unrealistic current distribution. In the smoothed distribution, allowance would have to be made for setting the current to zero at any unconnected wire ends.

The basis function used for this purpose is a three term sinusoidal one, containing constant, sine and cosine terms.

The near field of a constant current on a wire element is not analytically integrable and has to be numerically evaluated during the program execution as it is in the WIREGRID program. However the sine and the cosine terms of the basis function chosen for the new program can be analytically integrated for the near field on a straight element and do not need a large amount of extra computer time for numerical integration. Another point in favour of this basis function is that the current distribution in a thin wire is approximatly sinusoidal and so the basis function is a good approximation.

2.1 Theory

Consider a section of a wire structure made up of three segments as shown below, the centre one being the jth element and the two either side being the j + 1 and j - 1 elements.



There is one matchpoint at the centre of each element, and the current at the jth matchpoint is given by I_d. The length of the jth element is 2dj. The current distribution on the jth element is given by:

$$C_j\ (s) = a_j + b_j \sin\ (ks) + c_j \cos\ (ks) \ \ldots\ldots\ldots\ldots\ldots \quad 3$$

where s is the distance along the element from the matchpoint. It can be seen that at the jth matchpoint, (s = 0)

$$I_j = a_j + c_j = C_j\ (0)$$

In order to conform with Kirchoffs law the current on the j^{th} element at A would have to equal the current of the $j + 1^{th}$ element at the same point and also in order to give rise to a smooth distribution of current along the complete wire at least the first derivative of the current would have to be matched at the junction. For each element this gives rise to 5 boundary conditions to which each element current defined by its three coefficients has to be fitted. If each of these conditions is applied to a wiregrid the analysis becomes very complex and a simpler approach has been adopted.

The method which is used in the new program is as follows. The current on the jth element is extrapolated, along the wire, to the matchpoints of the elements connected to it at either end and set equal to the matchpoint currents of those elements. Therefore for each element of the complete wire structure there are three conditions imposed on the current distribution.

$$C_j\ (d_j + d_{j+1}) = I_{j+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4$$

$$C_j\ (-\ (d_j + d_{j-1})\ ) = I_{j-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 5$$

$$C_j\ (0) = I_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 6$$

Equations 4, 5 and 6 can be solved to give the current coefficients a_j, b_j and c_j in terms of the three matchpoint currents I_j, I_{j-1} and I_{j+1}. When calculating the field due to the j^{th} element, the constant, sine and cosine terms of the current have to be integrated

2.1 Theory (Contd)

separately and multiplied by a_j, b_j and c_j respectively [1] whereas, in the original WIREGRID program, only a constant current along the element provided the field [2]. Each of these three field terms contains the matchpoint currents of the j^{th}, $(j + 1)^{th}$ and $(j - 1)^{th}$ element and whenever the field is calculated for an element, the expression contains the matchpoint currents of elements joining it at the ends.

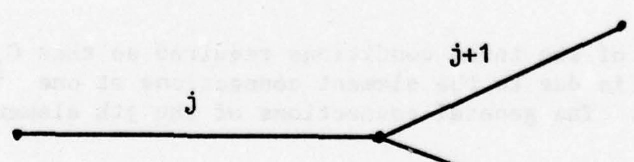
The mutual impedance matrix elements are the field components due to the matchpoint currents. The ij^{th} element of the matrix is the component of electric field tangential to the i^{th} wire element and calculated at its matchpoint from all electric field terms involving the matchpoint current I_j. These electric field terms have to be selected from the equations for the field due to element j and those connected to it. In this way all the elements in the matrix can be calculated, the solution of the matrix equation can then be found and the matchpoint currents obtained. It is then straightforward to recombine these currents to produce the coefficients a_j, b_j and c_j so that the complete current distribution on all the wires is known. From this known current at all points on the wire structure such quantities as the farfield radiation pattern and input impedance can be calculated.

2.2. Multiple Junction Treatment

The treatment of sinusoidal interpolation so far has been concerned with elements that are singly connected. This would be acceptable for modelling single wire antennae but the program is designed to deal with aerials on conducting vehicles, the surfaces of which are modelled by grids of wires. In these grids there are junctions at which many wire elements meet each other and thus there is need of a suitable multiple junction treatment. For WIREGRID this problem does not arise because each element is treated separately and there is no overlap of basis function from one element to another.

The method described below represents one possible way of dealing with multiple junctions and is the approach used in the new program.

For example, consider the jth element of a wire structure that has two equal length elements joined to it at one end.



The current on the jth element is extrapolated to the matchpoints of both of the connected elements. These two extrapolated currents, $C_j (d_j + d_{j+1})$ and $C_j (d_j + d_{j+2})$, are equal. The two connected elements will, however, share the current from the jth element equally between them and therefore the current at the matchpoints of these elements is equal to $C_j (d_j + d_{j+1})/2$. Equating this current to the corresponding matchpoint currents provides a boundary condition at each of the adjacement matchpoints, ie

$$\frac{C_j (d_j + d_{j+1})}{2} = I_{j+1} \quad \ldots\ldots\ldots\ldots\ldots \quad 7$$

$$\frac{C_j (d_j + d_{j+2})}{2} = I_{j+2} \quad \ldots\ldots\ldots\ldots\ldots \quad 8$$

More generally, if there are n wires all of equal length connected to the jth element at one end it can be seen that:-

$$\frac{C_j (d_j + d_{j+a})}{n} = I_{j+a} \quad \ldots\ldots\ldots\ldots\ldots \quad 9$$

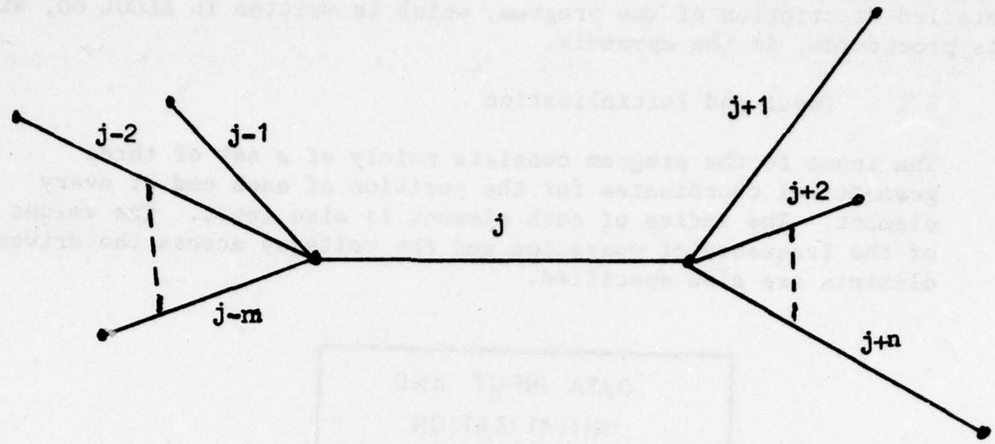
where $1 \leqslant a \leqslant n$

In order to be completely general, the example must be extended to include connected elements that differ in length, ie the d_{j+a} are not all equal. In this case the assumption is made that the boundary condition is obtained by replacing the current C_j in equation 9 with the average value of the current in the jth element extrapolated to each of the connected elements. This value is set equal to the sum of the matchpoint currents in the connected elements and the boundary condition is given by equation 10.

$$1/_n \sum_{\alpha=1}^{n} C_j (d_j + d_{j+\alpha}) = \text{Sum of currents}$$

$$= \sum_{\alpha=1}^{n} I_{j+\alpha} \quad \ldots\ldots\ldots\ldots \quad 10$$

This is one of the three conditions required so that C_j can be defined and is due to the element connections at one end of the jth element. The general connections of the jth element are shown below.



2.2 Contd

Therefore, the other two boundary conditions on C_j are provided by the elements attached to the other end, equation 11 and at the jth matchpoint, equation 12.

$$\frac{1}{m} \sum_{i=1}^{m} C_j \left(-d_j - d_{j-i}\right) = \sum_{i=1}^{m} I_{j-m} \quad \ldots\ldots\ldots\ldots\ldots \quad 11$$

$$C_j\,(0) = I_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 12$$

The three equations 10, 11 and 12 can be solved to give the current coefficients a_j, b_j and c_j in terms of $I_j, \sum I_{j+1}$ and $\sum I_{j-1}$. From these values the fields due to each element can be calculated and the contributions to these fields that form the mutual impedance matrix, can be extracted.

3. OUTLINE OF PROGRAM

The computer program that has been written uses the theory described in section 2, and the basic structure of the program is shown in the block diagram, fig 1. An outline of each block is given here and there is a detailed description of the program, which is written in ALGOL 60, with its procedures, in the appendix.

3.1 Input and Initialisation

The input to the program consists mainly of a set of three geometrical coordinates for the position of each end of every element. The radius of each element is also input. The values of the frequency of operation and the voltages across the driven elements are also specified.

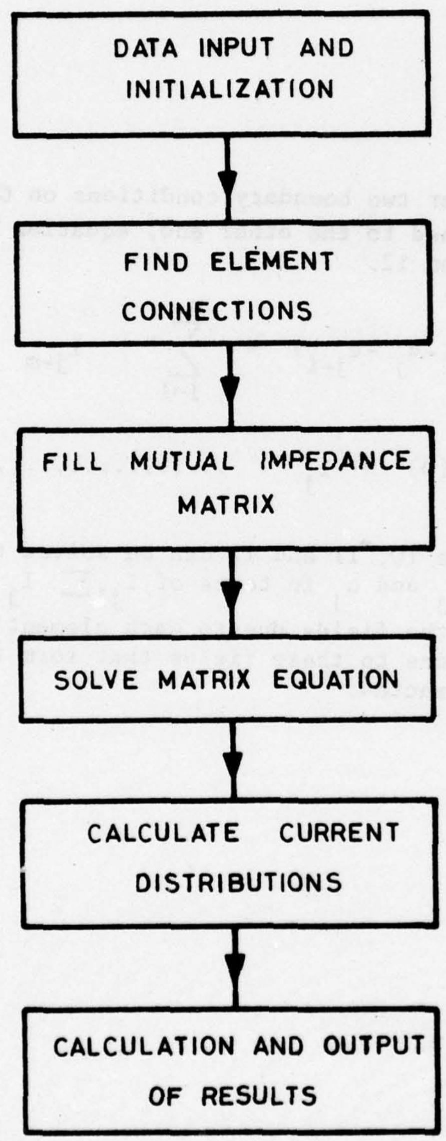


FIG. 1 BLOCK DIAGRAM OUTLINE OF PROGRAM

3.2 Element Connections

The connection of one element to another is not explicitly stated in the input data and so it is found from the coordinates. An element is taken as connected to another if the coordinates of their ends all agree to within $10^{-4}\lambda$.

3.3 Fill of mutual impedance matrix

The mutual impedance matrix is filled one row at a time. Therefore it is necessary to calculate the field due to every element at each of the matchpoints in turn. This involves the three field integrals for each element; the sine and cosine integrals can be analytically integrated whereas the constant integral uses a numerical technique. The correct contributions to each matrix element can then be found and added together in order to build up the matrix elements for one row of the matrix.

3.4 Matchpoint currents

The matchpoint currents are found by solving equation 2. The program uses a Gaussian Elimination method, for this purpose, which deals with two rows of the matrix at a time.

3.5 Calculation of Current Distributions

Once the matchpoint currents have been obtained, the current coefficients a_j, b_j and c_j for each element are found by recombining the matchpoint currents according to the original expressions for these coefficients.

3.6 Output

The output of the program is the complete set of matchpoint currents and also the current coefficients a_j, b_j and c_j. Separate calculations can then be performed on these values to produce the required electromagnetic characteristics. The program actually calculates the farfield radiation pattern in any plane and also the total radiated power.

4. RESULTS

These results are the preliminary work that has been done to verify the new program. In this section the original program that used the 'pulse current' basis function is referred to as WIREGRID 1 and the new sinusoidal interpolation program is called WIREGRID 2.

4.1 Program verification

Two methods have been used for checking the results produced by WIREGRID 2. The first of these is to compare its results with those produced by reliable analytic or experimental techniques. Secondly the performance of the program can be compared with other programs in terms of accuracy and the amount of computer time involved.

4.1 Contd

In the first of these two methods there are problems involved in finding dependable results because of the difficulty in analysing aerial systems other than simple linear cases. Therefore the first test used was that of a half-wave dipole, using the results produced by the King-Middleton second order theory [5] as a comparison. The second test used, was a monopole mounted on a conducting sphere, the wiregrid model of which contains two multiple element junctions. Semi-analytic results for this example have been produced by Tesche and Neureuther [4] and these were used for the comparison.

Some experimental measurements have also been made using copper models of aerial systems in anechoic chambers and outside model ranges, but there has been difficulty in obtaining consistent results when using different facilities.

Another question that arises when verifying these simulation programs is what characteristic to use to judge the quality of the results. For example, should the input impedance or the farfield pattern be used as a basis when optimising such variables as the number of elements or the wire radius. In the first test the comparisons have been made on the basis of impedance and in the second tests on the basis of farfield.

4.2 Comparison on the basis of impedance

The aerials that were modelled in this case were half-wave dipoles of various thicknesses. The aerial was represented by dividing it into an odd number of equal length elements, the centre one being driven by one volt across it. This model only involved junctions of two wire elements and therefore tested the sinusoidal interpolation but not the multiple junction treatment. The frequency of operation of the dipole was 49.18 MHz.

The King-Middleton second order results for the impedance of a half-wave dipole are shown in figs 2a and 2b. These are graphs of resistance against Ω and reactance against Ω, respectively,

$$\Omega = 2 \text{ Ln } (2h/a) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 13$$

where h is the aerial half length (ie $\lambda/4$)

and a is the aerial radius

Figs 3a and 3b show the resistance and reactance of halfwave - dipoles with $\Omega = 10$ calculated using both WIREGRID 1 and WIREGRID 2 for numbers of elements varying from 5 to 199. (This involved changing the original WIREGRID 1 which was current driven, to have a similar voltage source to that in WIREGRID 2). The King-Middleton theoretical values are also shown on the graphs.

For both resistance and reactance the curves for WIREGRID 2 adopt relatively slowly varying values within 20% of the theoretical value after approximately 25 elements whereas to achieve a similar result WIREGRID 1 requires 100 elements. However, it should be noted that the curves do not converge to a single value as the number of elements increase.

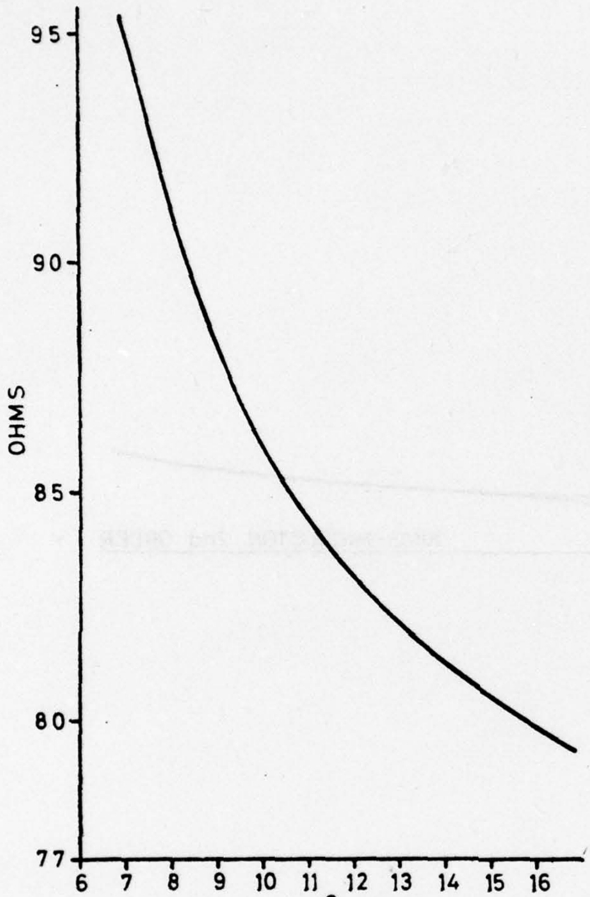


FIG. 2 (a) RESISTANCE

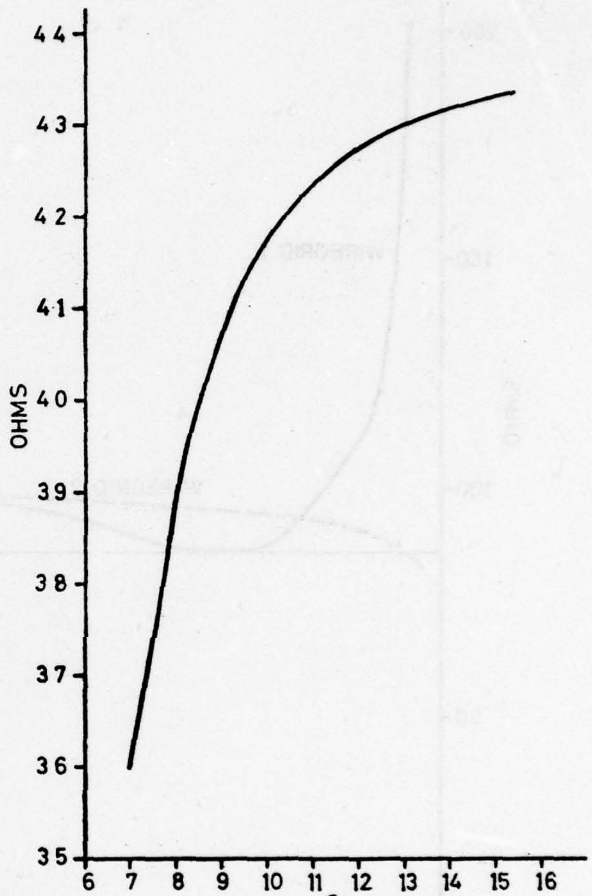


FIG. 2 (b) REACTANCE

IMPEDANCE OF HALF-WAVE DIPOLES WITH VARYING THICKNESS
KING-MIDDLETON SECOND ORDER APPROXIMATIONS

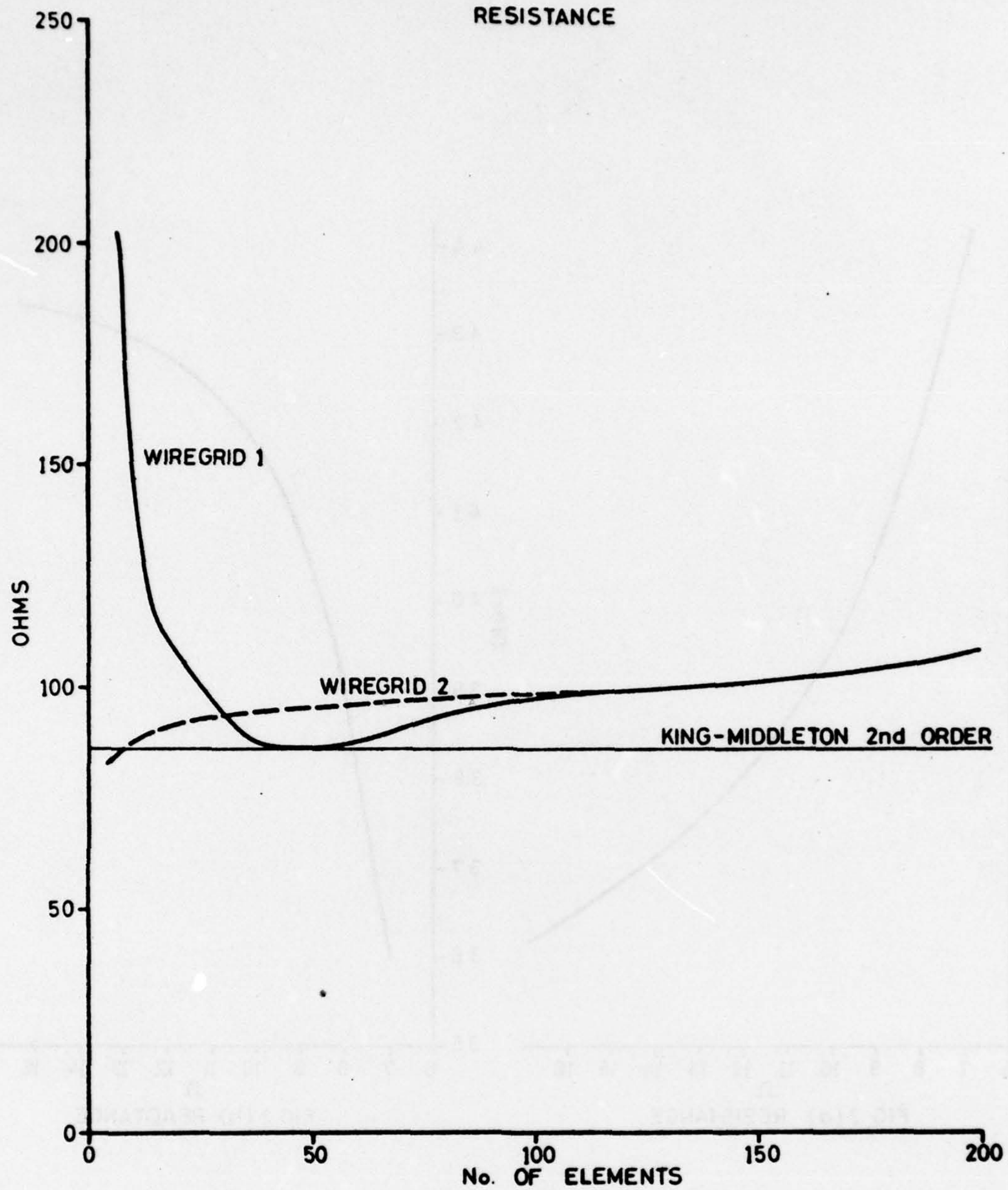


FIG. 3 a COMPARISON OF WIREGRID 1 AND WIREGRID 2 FOR A HALF-WAVE DIPOLE WITH $\Omega = 10$

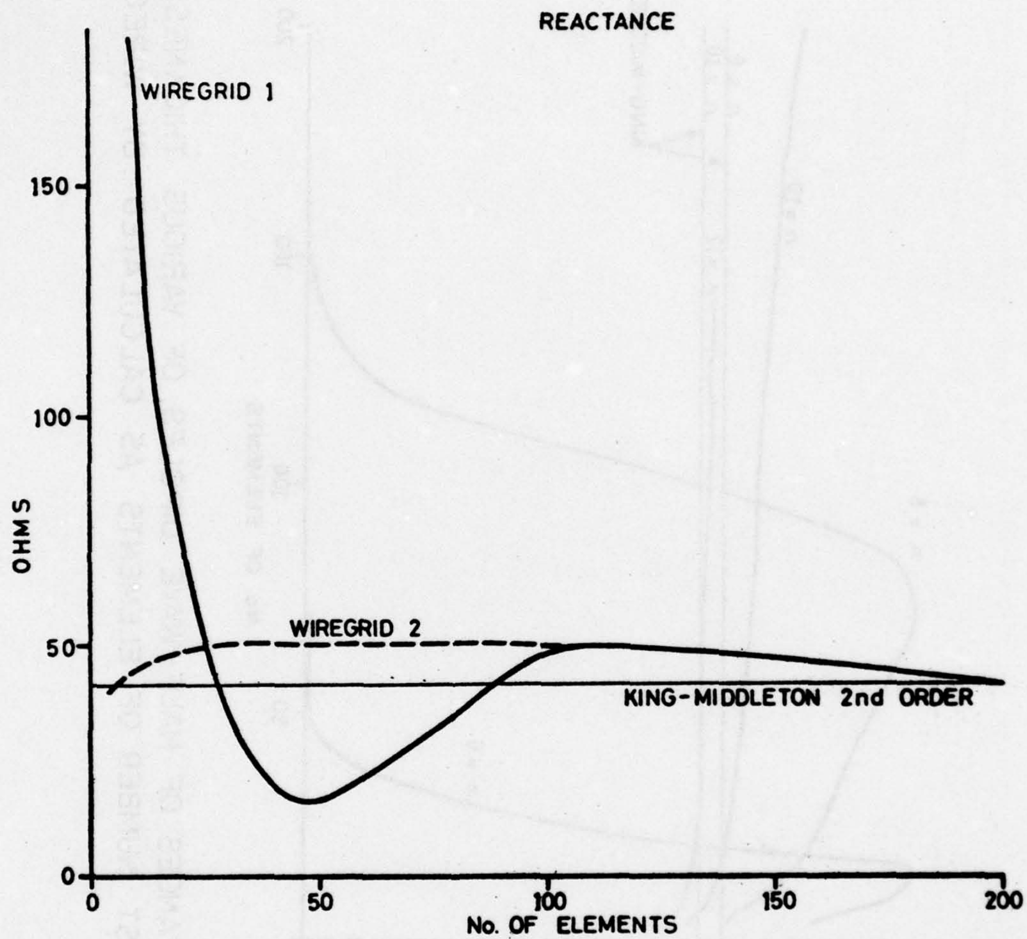


FIG. 3B COMPARISON OF WIREGRID 1 AND WIREGRID 2 FOR A HALFWAVE DIPOLE WITH $\Omega = -10$

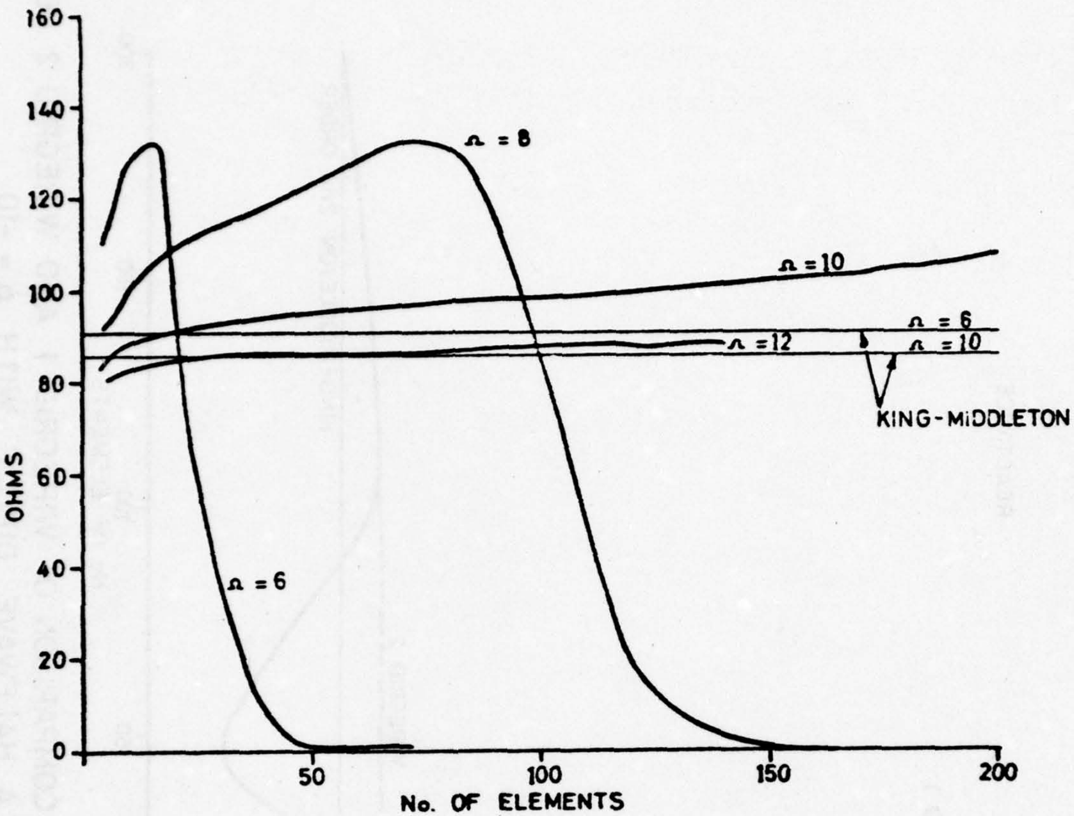


FIG. 4a RESISTANCES OF HALF-WAVE DIPOLES, OF VARIOUS THICKNESSES, PLOTTED AGAINST NUMBER OF ELEMENTS AS CALCULATED BY WIREGRID 2

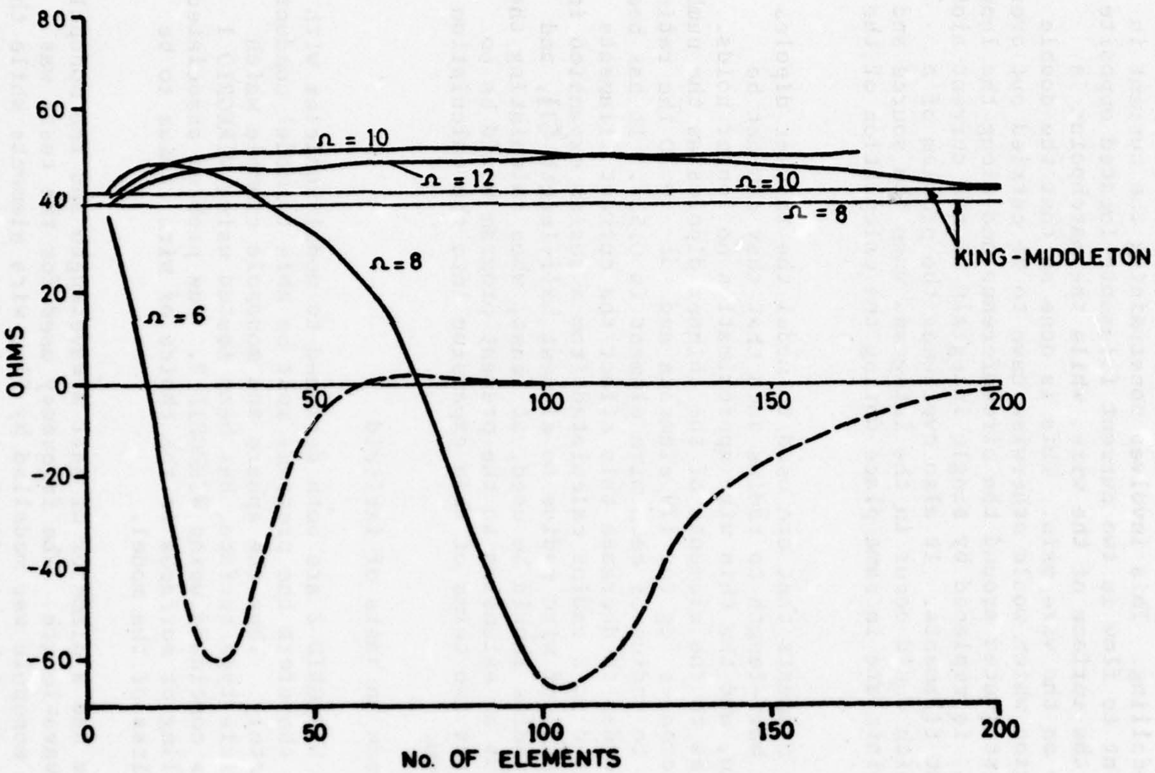


FIG.4B REACTANCES OF HALF WAVE DIPOLES, OF VARIOUS THICKNESSES, PLOTTED AGAINST NUMBER OF ELEMENTS AS CALCULATED BY WIREGRID 2

4.2 Contd

Figs 4a and 4b show impedances calculated using WIREGRID 2 for a number of values of Ω . These graphs show that for the thicker dipoles, Ω = 6 and 8. as the number of elements increase the impedance becomes erratic, but for Ω = 12 the convergence to a single value is much better. This problem of non-convergence with number of elements arises due to the thin wire approximation used in wiregrid modelling. This involves constraining the current in the wire element to flow in two current filaments located opposite each other on the surface of the wire, while the matchpoint is assumed to lie on the wire axis. This is done so that the double field integration which would otherwise have to be carried out over the current distributed around the circumference and along the length of the element, is replaced by single integrals of the current along the two current filaments. It also overcomes the problem of a singularity which would occur in the integrand when the source and observation points are in same place during the calculation of the self term.

Therefore, the elements that are used to model the thicker dipoles have ratios of half-length to radius such that they can not be considered thin, and the thin wire approximation no longer holds. The same applies to the elements of the thinner dipoles as the number of elements increases (eg for 129 elements and Ω = 10 the ratio of half-length to radius of each wire element is 0.58). It has been found that in order to decrease this effect the current filaments should be located at a radius calculated from a series expansion in terms of the ratio of wire radius to element half-length [3], and that this new radius should be used, at least, when calculating the self term. Thus an extension to the present program would be to include the first two terms of this expansion into the calculation of the self term.

4.3 Comparison on basis of farfield

WIREGRID 1 and WIREGRID 2 are both designed to model vehicles with their aerials, therefore the programs must be able to model conducting surfaces adequately. Thus the sphere and monopole example which provides a vehicle type surface, has been tested using WIREGRID 1 and these tests continued using WIREGRID 2. One problem associated with the modelling of surfaces is the choice of wire radius to be used for the wires of the model.

The sphere used had a diameter of half a wavelength and the monopole was a quarter wave-length. The frequency used for the tests was 24.6 MHz. The monopole was modelled by five wire elements while the sphere was made up of longitudinal wires divided into a number of equal length, straight elements. (The notation used is n * m which represents n longitudinal wires each divided into m elements). There are no lateral elements in this structure because no current flows in the lateral direction, due to the symmetry of the problem. The wire model for an 8 * 8 sphere is shown in fig 5 and the driven element is the one at the base of the monopole.

When using WIREGRID 1 the best fit to the farfield pattern produced by Tesche and Neureuther was found when the surface area of each

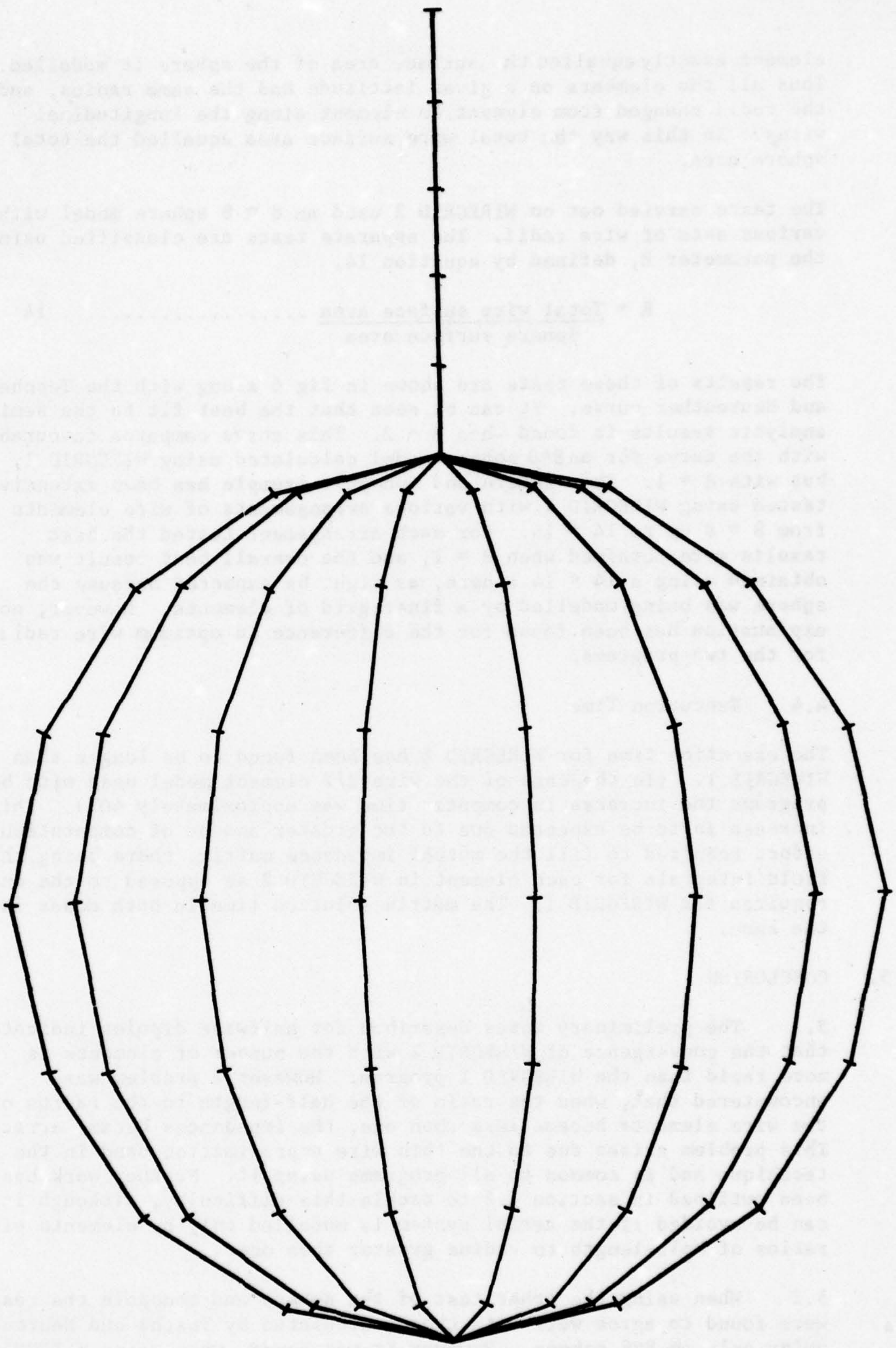


FIG. 5. 8 x 8 ARRANGEMENT OF WIRE ELEMENTS FOR A SPHERE

element exactly equalled the surface area of the sphere it modelled. Thus all the elements on a given lattitude had the same radius, and the radii changed from element to element along the longitudinal wires. In this way the total wire surface area equalled the total sphere area.

The tests carried out on WIREGRID 2 used an 8 * 8 sphere model with various sets of wire radii. The separate tests are classified using the parameter R, defined by equation 14.

$$R = \frac{\text{Total wire surface area}}{\text{Sphere surface area}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 14$$

The results of these tests are shown in fig 6 along with the Tesche and Neureuther curve. It can be seen that the best fit to the semi-analytic results is found when R = 2. This curve compares favourably with the curve for an 8*8 sphere model calculated using WIREGRID 1, but with R = 1. This sphere and monopole example has been extensively tested using WIREGRID 1 with various arrangements of wire elements from 8 * 8 up to 14 * 14. For each arrangement tested the best results were obtained when R = 1, and the overall best result was obtained using a 14 * 14 sphere, as might be expected because the sphere was being modelled by a finer grid of elements. However, no explanation has been found for the difference in optimum wire radii for the two programs.

4.4 Execution Time

The execution time for WIREGRID 2 has been found to be longer than WIREGRID 1. (In the case of the wire 277 element model used with both programs the increase in computer time was approximately 40%). This increase is to be expected due to the greater amount of computational effort required to fill the mutual impedance matrix, there being three field integrals for each element in WIREGRID 2 as opposed to the one required for WIREGRID 1. The matrix solution time in both cases is the same.

5. CONCLUSION

5.1 The preliminary tests described for halfwave dipoles indicate that the convergence of WIREGRID 2 with the number of elements is more rapid than the WIREGRID 1 program. However a problem was encountered that, when the ratio of the half-length to the radius of the wire elements became less than one, the impedances became erratic. This problem arises due to the thin wire approximation used in the technique and is common to all programs using it. Further work has been outlined in section 4.2 to tackle this difficulty, although it can be avoided if the aerial system is modelled only by elements with ratios of half-length to radius greater than one.

5.2 When using the other test of the sphere and monopole the results were found to agree well with those calculated by Tesche and Neureuther using only an 8*8 sphere. However it was found, when using WIREGRID 2, that the radii employed for the wire elements, to give the best fit gave the total surface area of the wires equal to twice that of the sphere they were modelling. Similar results to these were obtained using the WIREGRID 1 program also with an 8*8 arrangement of wires.

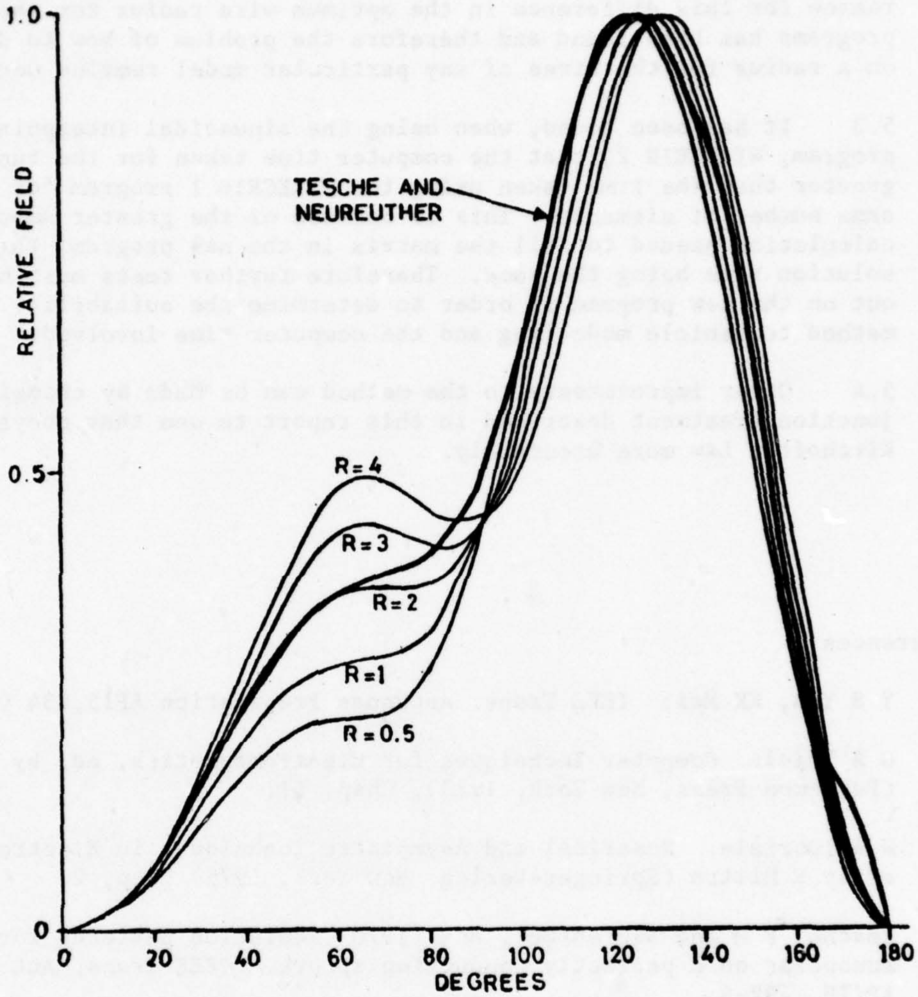


FIG.6 RADIATION PATTERNS FOR A SPHERE AND MONOPOLE

5.2 Contd

In this case the best wire radii used were such as to give the surface area of the wires equal to that of the sphere. No satisfactory reason for this difference in the optimum wire radius for the two programs has been found and therefore the problem of how to decide on a radius for the wires of any particular model remains unresolved.

5.3 It has been found, when using the sinusoidal interpolation program, WIREGRID 2, that the computer time taken for the runs is greater than the time taken using the WIREGRID 1 program for the same number of elements. This is because of the greater amount of calculation needed to fill the matrix in the new program; the matrix solution time being the same. Therefore further tests must be carried out on the new program in order to determine the suitability of the method to vehicle modelling and the computer time involved.

5.4 Other improvements to the method can be made by changing the junction treatment described in this report to one that obeys Kirchoff's Law more accurately.

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6. APPENDIX

This appendix describes the requirements of the new sinusoidal interpolation computer program and the basic functions of each of its procedures. It then gives details of the main program and new procedures including a list of variables used in each with their meanings.

1. Program Requirements and Structure

The original WIREGRID program was written in ALGOL 60 and implemented on an ICL 4130 computer. The new program is written in the same language for the same machine. The data input to the program is by paper tape and the output is via a line printer and paper tape punch. Once the mutual impedance matrix has been filled it is copied onto magnetic tape, so that it can be reclaimed in the event of a computer crash. The program also uses a disc pack for holding the updated matrix during the elimination process, and also for dumping the core store during a run.

1.1 Data Input

This takes place mainly in procedure SETUP although the input of frequency and numbers of elements takes place in the first part of the main program. The data structure is designed to be the same as WIREGRIDs, if old data tapes need to be used, but by making the frequency have a negative sign a slightly altered data structure is brought into action. This will read a radius with every new wire in the grid, instead of one radius at the end of the data tape for all wire elements. Also WIREGRID assumes that the aerial on the vehicle has a radius of 0.001λ and this can now be changed to any desired value. The input of all length values is in feet.

SETUP reads in the basic geometry data and sets up position and direction cosine arrays for each element. The input of the dump control character, the overall radius and the number of elements on the aerial, if they are present, takes place in the second part of the main program after the call of procedure SETUP.

Procedure JUNCTION is called from SETUP and this scans the geometrical data and picks out those elements that are connected together.

1.2 Matrix Fill

The calculations of the elements of the mutual impedance matrix are carried out by procedures ZMC and FIECON. The matrix is filled row by row; ZMC being the procedure that performs the integrations and calculations for the three field contributions from each matchpoint current a row at a time, FIECON then uses these values and combines them in the correct way to give the matrix elements. This matrix is written away to disk as each row is completed.

1.3 Solution to Equations

The solution to the equation represented by the impedance matrix is performed in procedure DISCGAUS. This is unchanged from the original WIREGRID version and has the same facility for dumping a partially solved matrix to magnetic tape. The solution is achieved using the Gaussian Elimination method and the complete array of matchpoint currents is determined.

1.4 Calculation of Current Distribution and Field Characteristics

Following the call of DISCGAUS the matchpoint currents have to be combined to produce the coefficients of the constant, sine and cosine terms in order that the current can be defined at all points on the wire. This takes place in procedure CURCOE. Once these values have been established the farfield radiation pattern can be calculated in procedure FARFIELD. Also the total power radiated can be calculated using the library integration procedure SIMPAD combined with FARFIELD. The call of FARFIELD used for this purpose occurs in the function POWER. This function is not set out with the other procedures but occurs in the block containing the calls of FARFIELD and CURCOE, the reason for this being the conservation of storage gained by only declaring the current coefficients in this block.

2. Program Description

2.1 MAIN PROGRAM

The main program is written in two parts: the first part, before the procedures, being initial data input and the declaration of global variables, the second part, after the procedures, is the control of procedure calls and subsidiary calculations.

In the first part the data input takes the form of the first 11 numbers of an old WIREGRID data tape, however at the present time the first three and the last four are only read as dummy values although they could be set up to control the farfield radiation calculations. The other four input values are the frequency in megahertz, the number of non-driven elements, the number of driven elements and the number of wires in the structure. These numbers are input right at the beginning of the program so that the array declarations are kept to their minimum size.

The second part of the main program begins by defining some constants used in the program and opening a disc-file for use by the program. The first procedure call (SETUP) is followed by the print out of the overall wire structure parameters and also the completion of data input with values of a dump control parameter and the number of elements on the actual aerial part of the wire structure, also if the frequency had been given a positive value, the radius for the grid structure. (In this case the radius for the aerial is set at .001 wavelengths). The rest of the main program controls the sequence of operations

2.1 Contd

and procedure calls necessary to fill the matrix, solve the equations and calculate field characteristics. The matrix is written away to disc as it is calculated a line at a time, in the main program, and also the dumping procedure during matrix fill is controlled at this point. In the WIREGRID program the dump of core only occurs in procedure DISCGAUS and the frequency of dumping was dependent on the value of the dump control parameter. In the new program the matrix fill takes longer than before and it is necessary to include provision for dumping in this part of the program. At present both the dumps have been rewritten to be independent of the dump control parameter, and instead depend on the state of sense key one. Dumping can be initiated by setting sense key one at any time during the filling of the matrix and the solving of the equations and the execution can be terminated after any dump. During DISCGAUS the dump is to disc (channel 101) while the contents of working space on disc are written to magnetic tape so that the run can be restarted later. During matrix fill the dump is simply a disc dump. Controlling dumps in this way gives the computer operator freedom to dump and if necessary terminate execution at any time in the main bulk of the program.

The rest of the main program calls the final procedures and calculates the total power output of the structure using the procedure SIMPAD. The output of the matchpoint currents to the lineprinter and also to the paper tape punch is in this part of the program. It must be noted that after the call of DISCGAUS there is no further provision for dumping the program and if a wire structure of 300 elements is being used the total power integration can take about an hour. However once DISCGAUS has finished and a record of the matchpoint currents has been obtained all further calculations can be put in subsidiary programs to calculate specific field values.

VARIABLE LIST FOR MAIN PROGRAM

WFT	Reciprocal of Wavelength in feet
TAD	Conversion factor from degrees to radians
FREQ	Frequency in megahertz
JJ	Total number of wire elements
J2J	Total number of element ends
NWIRE	Number of non-driven wire elements
NEL	Number of driven elements
NSEG	Number of wires in data structure
D	Dummy variable
AERIAL	Number of elements in aerial
X, Y, Z	Arrays containing element centre coordinates (λ)
SI	Arrays containing element lengths
CAB, SAB, SALP	Arrays containing direction cosines of elements
CURR, CURI	Arrays of matchpoint currents (real and imag.)
VOLTR, VOLTI	Arrays of right hand side of basic matrix equation, ie electric field tangential to centre of each element (real and imag.)
RADII	Array containing radius of each element
TP	2π
PI	π
ZZ	Z_o, the impedance of free space
WAVE	Wavelength in meters
CRY	$8\pi^2$
CCST	$180\pi^2/Z_o$
CH	Channel number for disc work space
TAGR	Flag to indicate whether old WIREGRID type data tape
C	Rows of matrix as written away to disc
J, I	Loop counters
BRAD	Wire radius for main structure
AR, BR, CR	Current coefficients a, b and c (Real)
AI, BI, CI	Current coefficients a, b and c (Imag.)
TOTPOW	Total power output

2.2 Procedure SETUP

This procedure is essentially the same as LINSEG from the original WIREGRID program, and its purpose is to read in the bulk of the input data to the program. The data consists of the wire grid geometry coordinates and the excitation voltages. The data is divided into two parts, the first concerning the wires that have an unknown voltage across them and the second those wires that are driven with a voltage and are the sources of the structure. The division arises because the method of input in the two cases is different.

For the non-driven wires the procedure reads the coordinates of the endpoints of each wire and also the number of elements that go to make up the wire. It will also read the radius for each wire if one is present. In order to specify the presence of a separate radius for each wire the value of the frequency is set to be negative. This is detected on input and a flag is set to indicate that a value for the radius of each wire must be read off the data tape. If the frequency is left as a positive number the data tape takes the form of an ordinary WIREGRID tape, thus enabling old data tapes to be reused in the new program.

After reading the information for each wire the program calculates the length of each element and the coordinates of the centre point in units of wavelength, and also its direction cosines are evaluated. The array containing the tangential fields at the matchpoint of the element is set to zero. The coordinates of the end of each element are found and stored in arrays, however in order to save on the considerable storage needed to retain this information, there being 6 coordinates to each element, the arrays are only declared in this procedure. These arrays are used by procedure JUNCTION in finding the elements that are connected, thus the call for JUNCTION has to be inside SETUP.

Procedure SETUP deals with the output of the geometry information in the form into which it has been rearranged. The order of output is as follows:-

(1) the position of the element in the input data (segment no.)
(2) the number assigned by JUNCTION to the first of its ends
(3)-(5) the coordinates of this end
(6) the number of the next end connected to it (B(END))
(7)-(11) corresponding data (items 1-6) for its other end
(12) the length of the element
(13) the element radius, if the input frequency is negative.

All values which have the dimensions of length are printed in wavelengths unless otherwise stated. The input of the driven wire elements takes place after the non-driven ones, but still in procedure SETUP. This represents a departure from the original WIREGRID program which read the known element data in the main program after the call of LINSEG, however all the element geometry data input is now in one procedure. (The only exception to this is the input of the radius for the whole wire structure and the number of elements in the aerial which is still in the main program if the frequency is positive). The data for driven elements takes the

following form; the coordinates of the centre point of the element, its length, two orientation angles (the first being the angle up from the z = 0 plane and the second being the angle round from the x axis in the z = 0 plane) and finally the real and imaginary parts of the driving voltage. Each driven element has to be input separately and cannot be specified as part of a long wire.

All input data takes place at the beginning of the program, SETUP being the first procedure called, and so any errors in the data, if they are detectable, will be found and program execution will terminate before large amounts of computer time are wasted on useless calculations. It should be noted that the current in the wire elements is assumed by the program to flow in the direction in which the end coordinates are read, and also that, whereas the old WIREGRID program inputs the current in the known current elements, the new program reads the voltage that is across the driven element and uses this in the right hand side of the matrix equation causing the current distribution in this element to be calculated in the same way as the other elements. The calculation of the input impedance is then a simple matter as the current and voltage, on the driven element, are known.

VARIABLE LIST FOR SETUP

XX, YY, ZZ	Arrays containing coordinates of element ends.
X, Y, Z	Arrays containing coordinates of element midpoints.
X1, Y1, Z1	Coordinates of first end of input wires.
X2, Y2, Z2	Coordinates of second end of input wires.
CCAB, CSAB, SAL	Arrays containing x, y and z direction cosines of elements.
NINC	Number of elements per input wire.
JJ	Total number of elements.
NW	Number of non-driven input wires.
WFT	Reciprocal of wavelength in feet.
SI	Array containing lengths of elements (λ)
I, J	Loop counters.
N	Element number counter.
VOLTR, VOLTI	Arrays containing voltages across elements.

Other variables are either global or just intermediate values in the calculation.

2.3 Procedure JUNCTION

This procedure is called from procedure SETUP and is used to determine which element ends are connected to each other. The connection data is held in an array of length twice the number of elements. There is one element of the array for each end. The subscript of the array corresponds to the number of the end being considered, and the contents of that array element the number of an end connected to it. To begin with all the elements of the array are set to contain their own subscripts, eg B [5] = 5. In this way all the ends are connected to themselves only.

Each end is then taken in turn and its coordinates are compared with those of all the ends following it. The criterion for two coordinates to overlap is that their difference is less than $10^{-4}\lambda$. If any of the coordinates are found to differ the comparison ceases and the next end is compared. In this way by making the difference between the coordinates of any two ends just greater than $10^{-4}\lambda$ they can be virtually at the same place and not electrically connected. If any other end is found at the same position to within the specified criterion, the number of this end is placed in the element of the array that corresponds to the original end. Thus the value in the connection array element is the number of the next connected end. After a successful comparison or no coincident end has been found, the process is repeated for the next end, but the comparisons are only made with those element ends that follow it in the sequence, so that no comparison is made twice.

The end product of this procedure is the array B which contains all the connection data. Opposite ends of the same element are given numbers that are separated by the total number of elements. A complete set of connected ends can be found by taking the number of one end and accessing the number contained in its array element, this will point to the next connected end, and using its number to access the array, the next end can be found. This can be continued until the array element points back to the original end showing that all the connected ends have been found. Thus all the connected ends are chained together in the connection array, the last element of the chain pointing back to the starting position.

VARIABLE LIST FOR JUNCTION

XX, YY, ZZ	Arrays containing coordinates of ends
N	Number of ends
M	Number of ends minus one
I,J,K	Loop counters
B	Array containing connection data

2.4 Procedure FIECON

This procedure determines the elements of the mutual impedance matrix from the output of ZMC combined with information from the connection array and the lengths of the elements. For each call of the procedure one complex element of the matrix is returned. The position of the calculated element in the matrix is the Jth column in the row being considered. J is an input parameter to the procedure. In the main program the rows are looped over in turn, ZMC producing a set of integrals for the complete row, the columns being processed one by one for each row with a call of FIECON for each element.

FIECON must therefore produce all the field terms which have a dependance on a given matchpoint current I_j and sum them while that particular element of the matrix is being considered. It is necessary for the procedure to be able to identify the elements which are connected together, therefore the second of the input parameters is the junction array, B.

The equations that define the field due to the Jth element are as follows with three components, the fields due to I_j and those due to the sums of the matchpoint currents at either end of the Jth element.

$$G(I_j)=\left[(S_{j+1}C_{j-1}+S_{j-1}C_{j+1})I_jX_j(r) + (nC_{j-1}-mC_{j+1})I_jY_j(r) + (S_{j-1})I_jZ_j(r)\right]/H \quad .. \; 15$$

$$G\left(\sum_{i=j+1}^{j+n} I_i\right)= \left[nS_{j-1} \sum_{i=j+1}^{j+n} I_iX_i(r) + n(m-C_{j-1}) \sum_{i=j+1}^{j+n} I_iY_i(r) - nS_{j-1} \sum_{i=j+1}^{j+n} I_iZ_i(r)\right]/H \quad .. \; 16$$

$$G\left(\sum_{i=j-1}^{j-m} I_i\right)= \left[mS_{j+1} \sum_{i=j-1}^{j-m} I_iX_i(r) - m(n-C_{j+1}) \sum_{i=j-1}^{j-m} I_iY_i(r) - mS_{j+1} \sum_{i=j-1}^{j-m} I_iZ_i(r)\right]/H \quad ... \; 17$$

Where $G(I_j)$ is the field due to the matchpoint current I_j. S and C are the sums of sines and cosines ($\sin k(d_i + d_j)$ and $\cos k(d_i + d_j)$ respectively, the subscript referring to the relevant end. X_i, Y_i, $Z_i(r)$ are the field integrals (as produced by ZMC) at a distance r, due to the constant, sine and cosine terms of the current expansion on the i^{th} element.

2.4 Contd

$$H = \left[mS_{j+1} + nS_{j-1} - \left(C_{j-1}\, S_{j+1} + C_{j+1} S_{j-1} \right) \right] \qquad \ldots\ldots\ldots\ldots \quad 18$$

The field from the matchpoint current I_j on the element J is straightforward and is given by equation 15. In order to obtain the other field contributions it is necessary to use equations 16 and 17, but taken when referring to the elements at either end. The sums of matchpoint current will then be seen to contain the term I_j. Using the equations with just the I_j terms from the summations will produce the extra contributions to the total field from I_j.

The order in which this procedure carries out the calculations is to deal with one end of the Jth element at a time and calculate the sine and cosine term for that element with one of the connected elements. The same thing is done with the connected element, finding the sum of sines and cosines for elements connected to both its ends. This whole procedures is repeated for each element connected to the particular end of the Jth element and in a similar way the elements at the other end of Jth element are dealt with. The connection data is found by accessing the junction array B and examining the contents of the array element that corresponds to the end being considered, the value found will point to the next end connected at that junction or else back to the original end, signifying all joined elements have been used.

When the values of the sine and cosine summations have been found they are inserted in the correct formulae and combined with the respective output of ZMC to produce a contribution to the procedure return parameters. For the special case where no elements are connected to a particular element end the sine and cosine are evaluated at the end point of the element and there is no contribution from the field equation for that end (the sums of matchpoint currents being zero). This means that the current goes to zero at the end because there are no elements there to continue the current. The whole procedure is outlined in the flow diagram (fig 7).

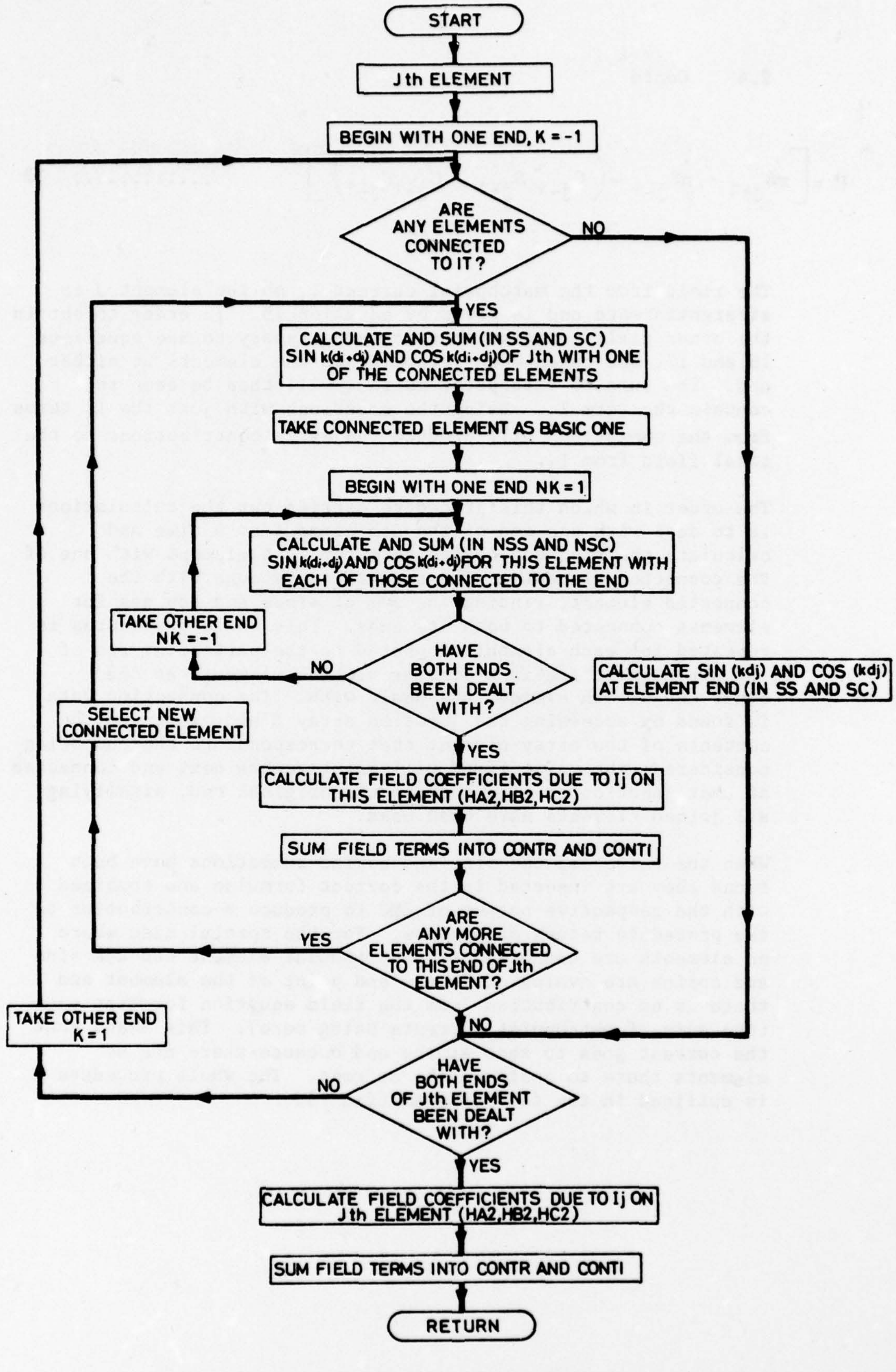


FIG. 7 FLOW DIAGRAM OF PROCEDURE FIECON

VARIABLE LIST FOR FIECON

J	Main element number
J2	Main element end number
JT	Connected element number
NJ2	Connected element end number
NUM, NUM2, NN1, NN	Intermediate end numbers
SS, SC	Main element sine and cosine summations
NSS, NSC	Connected element sine and cosine summations
K, NK	Define which end of main and connected elements being used
KD, ANG	$k(d_i + d_j)$
S	Length of Jth element
SJT	Length of connected element
SSO, SCO	Sums of sines and cosines of main element (K = -1 end)
NSSO, NSCO	Sums of sines and cosines of connected element (NK = -1 end)
N, M	Number of elements connected to ends of main element
N2, M2	Number of elements connected to ends of connected element
NEG	Current sign indicator due to direction of element
H	Field contribution equation divisor
HA2, HB2, HC2	Field contribution coefficients for constant, sine and cosine terms
CONTR, CONTI	Real and imaginary parts of final matrix element
TSC	Intermediate variable

2.5 Procedure CURCOE

The purpose of this procedure is to calculate the values of the coefficients a, b and c for the current distributions on each element. CURCOE achieves this by using the arrays of matchpoint currents calculated by DISCGAUS, which are the first two input parameters of the procedure. Each of the wire elements is dealt with in turn in the program; as in procedure FIECON one end of the element is selected first. A junction array (JUNC) is filled by accessing the main connection array B, and storing the connected end numbers. This new junction array is a two dimensional one, the first subscript referring to the end of the main element to which the other elements are connected. The second subscript is incremented for each new connected end, the zeroth value array element being set to contain the total number of elements joined to the end being considered.

This junction array is used to provide the numbers of the connected ends in turn, so that the summations of their sin $K(d_i + d_y)$ and cos $k(d_i + d_j)$ terms and the matchpoint currents can be found. The procedure also takes into account the direction of the joined elements so that the matchpoint current can have the correct sign. (The whole program assumes that the current is flowing in the direction in which the coordinates of an element are input). If there are no connected elements at a particular end the variables (SUMR and SUMI) which contain the summation of matchpoint currents are set to zero and the sine and cosine terms are evaluated at the end point. However, the number of elements connected to the end is not set to zero but is given the value one. This can be interpreted as a zero length element with no current flowing in it connected to the end.

This complete process is repeated for the other end of the element so that a complete set of summations is obtained. The coefficients for the sums of matchpoint currents in the equations for a, b and c are calculated and multiplied by their respective sums of currents to produce the values a, b and c. These are stored in 6 arrays, there being a real and imaginary part to each coefficient, and these arrays are available for the calculation of the farfield patterns. The values of a, b and c are printed out at the end of this procedure for each element in the wire grid.

VARIABLE LIST

JUNC	Junction array (2 dimensional)
JC	Wire element number
J2	Element end number
I	Connected end counter
SUMR, SUMI	Sums of matchpoint currents (Real and imag)
SS, SC	Sums of sines and cosines
NEG	Current sign indicator due to direction of element
II	Counter for loop over connected elements
JT	Connected element end no
K	Main element end indicator
DIST	Distance between adjacent matchpoints
KD	$k(d_i + d_j)$
N, M	No of elements connected to either end of main element
H	General divisor
HA1, HA2	Coefficients in equation for a_j
HB1, HB2, HB3	Coefficients in equation for b_j
HC1, HC2	Coefficients in equation for c_j
AR, AI, BR, BI, CR, CI	Arrays containing a, b, c (Real and Imag)

2.6 Procedure ZMC

This procedure calculates the axial electric field at one element due to unit, unit cosine and unit sine currents flowing in another.

The current is assumed to flow on the surface of an element only in the axial direction. This is a good assumption if the program is being used to model wire antennas and, if a surface is being modelled, perpendicular elements in the wiregrid carry the perpendicular current. To avoid integrating the axially directed surface current around the wire circumference a further approximation is made that current only flows in two filaments spaced a wire radius from the plane containing the observation point and the wire axis. See fig (ZMC 1). Again this approximation is not worrying considering the approximations of wiregrid modelling. Expressions to be integrated are found by multiplying the field of a current element by 1, cos (ks) or sin (ks). The near field of sinusoidal currents can be integrated analytically and can be found in books by Stratton and Weeks. A slight modification is necessitated by the geometry of the displaced filaments of Fig (ZMC 1). [6] The constant term integrations and geometrical factors follow closely the WIREGRID program to be found in [2] with the following exception necessitated by accuracy considerations. The sinusoidal interpolation used can be thought equivalent to a Power series expansion when x is small

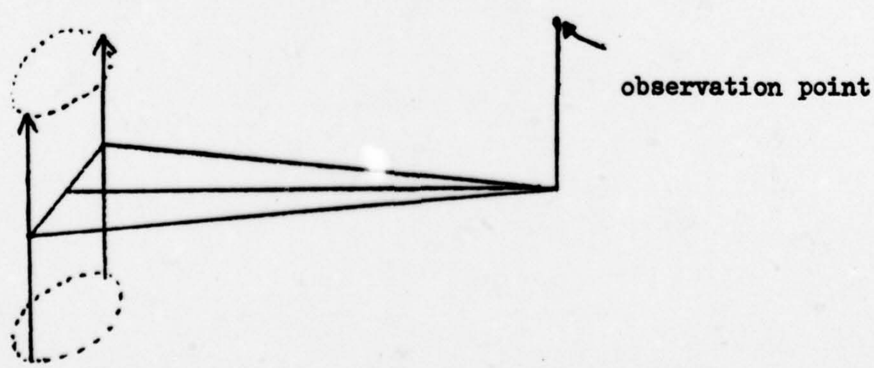
$$1 \equiv 1$$

$$X \equiv \sin x$$

$$X^2 \equiv 2(1 - \cos x)$$

and considerable loss of accuracy can and does occur on subtracting the 1 and the cos terms since they are nearly equal and the 1 term is evaluated by an approximate numerical method. ZMC therefore integrates only the difference term $(1 - \cos x) = 2 \sin^2 x/2$ which is small and adds the answer to the more exact COS TERM. The 5 or 9 point Newton - Cotes method of WIREGRID was retained since it is now more than adequate. Adaptive schemes could be used but tend to be more time consuming and gaussian integration does not evaluate the integrand at its end points this being required for use in the sinusoidal terms.

FIG ZMC 1



circumference of wire is shown dotted.

2.6 Contd

The radial term of the constant term integration can also be done analytically [6].

For completeness the nearfields of sinusoidal current filaments are

COS TERMS

$$E_z \text{ REAL} = -k \sin(ks) \frac{\sin kR}{R} - k\cos(ks) \frac{(z-s)}{R} \frac{1}{R}\left(\frac{\sin(kR)}{kR} - \cos(kR)\right)\Bigg|_{-s}^{s} \qquad \ldots\ldots\ldots\ldots 19$$

$$E_z \text{ IMAG} = -k \sin(ks) \frac{\cos(kR)}{R} - k\cos(ks) \frac{(z-s)}{R} \frac{1}{R}\left(\frac{\cos(kR)}{kR} + \sin(kR)\right)\Bigg|_{-s}^{s} \qquad \ldots\ldots\ldots\ldots 20$$

$$E_\rho \text{ REAL} = \frac{1}{\rho}\left(k\sin(ks) \frac{\sin(kR)}{R}(z-s) - k\cos(ks)\left(\frac{\rho^2}{R^2} \frac{\sin(kR)}{kR} + \frac{(z-s)^2}{R} \cos(kR)\right)\right)\Bigg|_{-s}^{s} \qquad \ldots 21$$

$$E_\rho \text{ IMAG} = \frac{1}{\rho}\left(k\sin(ks) \frac{\cos(kR)}{R}(z-s) - k\cos(ks)\left(\frac{\rho^2}{R^2} \frac{\cos(kR)}{kR} - \frac{(z-s)^2}{R} \frac{\sin(kR)}{R}\right)\right)\Bigg|_{-s}^{s} \qquad \ldots\ldots 22$$

SIN TERMS

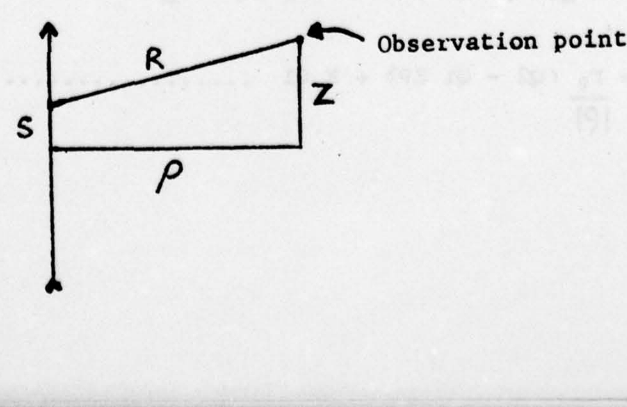
$$E_z \text{ REAL} = k\cos(ks) \frac{\sin(kR)}{R} - k\sin(ks) \frac{(z-s)}{R} \frac{1}{R}\left(\frac{\sin(kR)}{kR} - \cos(kR)\right)\Bigg|_{-s}^{s} \qquad \ldots\ldots 23$$

$$E_z \text{ IMAG} = k\cos(ks) \frac{\cos(kR)}{R} - k\sin(ks) \frac{(z-s)}{R} \frac{1}{R}\left(\frac{\cos(kR)}{kR} + \sin(kR)\right)\Bigg|_{-s}^{s} \qquad \ldots\ldots 24$$

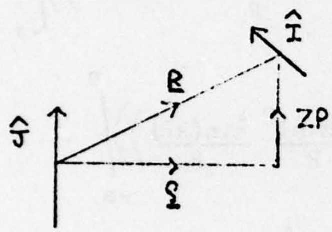
$$E_\rho \text{ REAL} = \frac{1}{\rho}\left(-k\cos(ks) \frac{\sin(kR)}{R}(z-s) - k\sin(ks)\left(\frac{\rho^2}{R^2} \frac{\sin(kR)}{kR} + \frac{(z-s)^2}{R} \frac{\cos(kR)}{R}\right)\right)\Bigg|_{-s}^{s} \qquad \ldots 25$$

$$E_\rho \text{ IMAG} = \frac{1}{\rho}\left(-k\cos(ks) \frac{\cos(kR)}{R}(z-s) - k\sin(ks)\left(\frac{\rho^2}{R^2} \frac{\cos(kR)}{kR} - \frac{(z-s)^2}{R} \frac{\sin(kR)}{R}\right)\right)\Bigg|_{-s}^{s} \qquad \ldots 26$$

$$\text{where } R = \rho^2 + (z-s)^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 27$$



The self term integration is different from the constant term. This follows exactly the WIREGRID PROGRAM ie the substitution $\tan\theta = s/a$ where a is the wire radius, is made and $\cos\left(\frac{ka}{\cos\theta}\right)$ is expanded and integrated term by term. Terms higher than $(ka)^6$ are neglected. Other possibilities for the self term when the element is modelling a surface have been considered such as replacement by the field at a patch that the element is representing. The geometrical factors and variables are best explained by reference to the fig (ZMC 2).



J is source element (unit vector)

I is observation (unit vector)

ρ is radial Coordinate vector of observation point

ZP is Z coordinate of observation

fig (ZMC 2)

clearly

$$\hat{\rho} = \frac{\underline{R} - (\underline{R}.\hat{J})\hat{J}}{|\rho|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 28$$

$$\underline{E} = E_\rho \rho + E_z \hat{J} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 29$$

$$\therefore \text{E along I} = \underline{E}.\hat{I}$$

$$= E_\rho(\hat{\rho}.\hat{I}) + E_z(\hat{J}.\hat{I})$$

$$= \frac{E_\rho}{|\rho|}\left(\underline{R}.\hat{I} - (\underline{R}.\hat{J})(\hat{J}.\hat{I}) \right) + E_z(\hat{J}.\hat{I})$$

If $ZP = \underline{R}.\hat{J}$, $Q1 = \hat{I}.\hat{J}$ and $Q2 = \underline{R}.\hat{I}$

$$E = \frac{E_\rho}{|\rho|}(Q2 - Q1\ ZP) + E_z Q1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 30$$

VARIABLE LIST

D	Array of Newton - Cotes Multipliers
ZKR, ZKI	Arrays of Constant Term Real and Imaginery Parts
ZCR, ZCI	Arrays of Cosine Term
ZSR, ZSI	Arrays of Sin Term
FKR, FKI	Used as field of known elements

TP = 2π

PI = π

ZZ = Impedance of free space

CCST Newton Cotes Nomalization constant

BK = Ka

BK2 = $(Ka)^2$

BK4 = $(Ka)^4$

CRYPT = $ZZ/4\pi$

T Variable of integration along element

EZRC C stands for COS, R for Real, Z for Ez

EPIS etc S for SIN, I for Imaginary, P for E_ρ

2.7 Procedure Power

This is a short "real" procedure which is used to return the single value of the power radiated in one specific direction. The procedure is used in conjunction with the call of SIMPAD (a library numerical integration routine) to integrate the power transmitted from the wire grid. The angles theta and phi (spherical coordinates) must be specified in radians in ATHET and APHI, these are then converted to degrees and used in a call of FARFIELD. (The first parameter in FARFIELD's list is set to zero so that there is no lineprinter output from this call). The value of POWER is calculated by squaring and summing the magnitudes of the fields in theta and phi directions and multiplying the result by sin (theta). This is obtained from the equation.

$$\text{Power} = \int_0^{2\pi} \int_0^{\pi} (\underset{\sim}{E} \times \underset{\sim}{H}^*)\, ds \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ 31$$

$$\text{Where } ds = \sin\theta\, d\phi\, d\theta \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ 32$$

The final value for the total power output is found in TOTPOW which is the result of the double integral performed on the output of procedure POWER divided by the impedance of free space. *The print out of this value occurs in the main program.*

VARIABLE LIST FOR POWER

ATHET, APHI	Field direction in radian (Input)
BTHET, BPHI	Field direction in degrees
POWER	Procedure value for power integration

2.8 **Procedure Farfield**

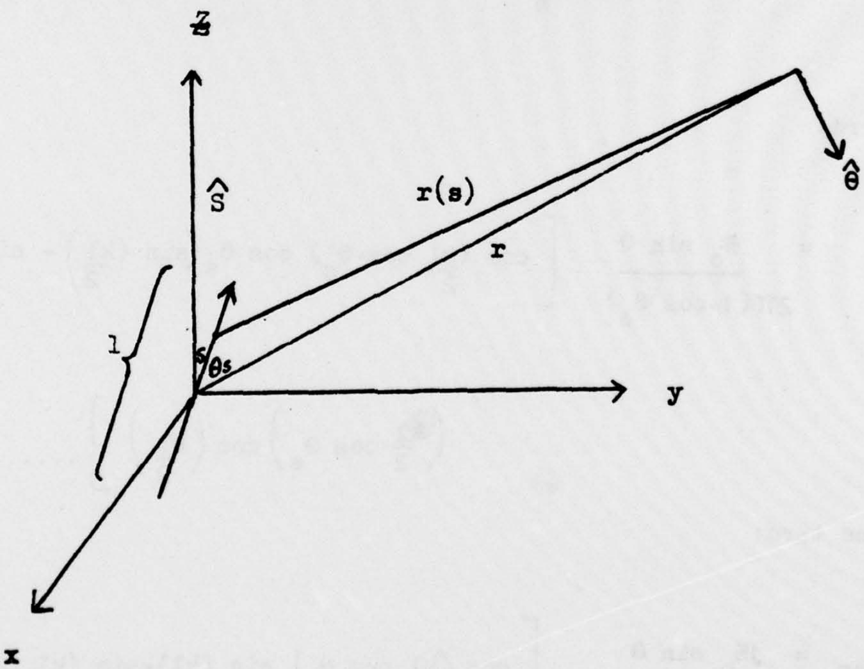
The purpose of this procedure is to calculate farfield radiation values. These can be found along any latitudinal or longitudinal circle or arc centred on the origin, or alternatively the field in any single direction can be found. The farfield is calculated in the theta and phi directions (spherical coordinates) because there is no radial component of field. For a short wire element centred on the origin with a current distribution I(s) the field at a distance r from that element is:-

$$E_\theta = \frac{j Z_o (-\hat{S}.\hat{\theta})}{2r \lambda} \int_{-l/2}^{l/2} I(s)\, e^{-jkr(s)}\, ds \quad \ldots\ldots\ldots\ldots 33$$

where $\hat{S}$ is the unit vector in the direction of the element

s is the distance along the element (from centre)

l is the length of the element



$$r(s) = r - s \cos \theta_s \quad \ldots\ldots 34$$

E_ϕ can be found by replacing $-\hat{S}.\hat{\theta}$ by $-\hat{S}.\hat{\phi}$.

For the farfield of the elements the value of r is very large and the dependence of the equation upon it can be neglected. Therefore the field is now:-

$$E_\theta = \frac{j Z_o (-\hat{S}.\hat{\theta})}{2} \int_{-l/2}^{l/2} I(s)\, e^{-jks\cos\theta_s}\, ds \qquad \text{.............. } 35$$

The current distribution has three terms and when substituted in the integral all three can be analytically evaluated.

(i) Constant current term:

$$E_{\theta\, const} = \frac{j Z_o \sin\theta \sin\left(k\frac{l}{2}\cos\theta_s\right)}{\cos\theta_s} \qquad \text{.............. } 36$$

(ii) Sine term:

$$E_{\theta\, sin} = \frac{Z_o \sin\theta}{2\pi(1-\cos^2\theta_s)}\left[\cos\left(\frac{kl}{2}\cos\theta_s\right)\cos\theta_s\left(\sin\left(\frac{kl}{2}\right) - \sin\left(\frac{kl}{2}\cos\theta_s\right)\cos\left(\frac{kl}{2}\right)\right)\right] \qquad \text{........ } 37$$

(iii) Cosine term:

$$E_{\theta\, cos} = \frac{jZ_o \sin\theta}{2\pi(1-\cos^2\theta_s)}\left[\cos\left(\frac{kl}{2}\cos\theta_s\right)\sin\left(\frac{kl}{2}\right) - \sin\left(\frac{kl}{2}\cos\theta_s\right)\cos\theta_s\cos\left(\frac{kl}{s}\right)\right] \qquad \text{...... } 38$$

2.8 Contd

The elements of the wire grid are not all centred on the origin and this means an extra factor of $e^{j\,k.R}$ (where R is the vector from the origin to the segment centre) must be introduced into the equations. The fields from each element are found by multiplying each term by the appropriate current coefficient a, b or c.

The procedure has as input parameters two values each of theta and phi which define the limits between which the direction of the farfield is stepped in increments of the fifth and sixth input parameters. The other procedure parameters are the arrays containing the current coefficients. The procedure contains two nested loops, the outer of which varies the values of theta while the inner loop changes phi. It is then straightforward to compute the values of the farfield due to the three current terms and sum them together. It should be noted that in order to over-come computational difficulties in the program, the denominator of each of the field expressions is set to have a minimum magnitude of 10^{-8}. (A similar problem occurs when the phases of the field values are being calculated and for this purpose a minimum magnitude of 10^{-10} is imposed upon the real part of the field). The input parameters, theta and phi are in degrees.

The results of this procedure are printed on the lineprinter in the form of the angles theta and phi in degrees followed by the fields in the phi and theta directions in terms of real and imaginary parts followed by their phases and magnitudes.

VARIABLE LIST FOR FARFIELD

CABI, SABI, SALPI	Direction cosines of elements
THET 1, THET 2 DTHET	Start and stop angles in theta directions Theta step size
PHI 1, PHI 2 DPHI	Start and stop angles in phi direction Phi step size
FZRTR, FZRTI FZRPR, FZRPI	Field in theta direction (real and imag.) Field in phi direction (real and imag.)
CTH, STH CPH, SPH	Cos and sin (theta) Cos and sin (phi)
SITHE, SIPHI	$-(\hat{\underset{\sim}{S}}.\hat{\theta})$, $-(\hat{\underset{\sim}{S}}.\hat{\phi})$
COTHES	$\cos\theta_s$
BETAZ, BET	πl, $\pi l \cos\theta_s$
KDOTR COSKR, SINKR	$\underset{\sim}{k}.\underset{\sim}{R}$ cos and sin $(\underset{\sim}{k}.\underset{\sim}{R})$
EXAR, EXAI, EXBR, EXBI, EXCR, EXCI	Real and imag parts of a, b and c multiplied by $j\underset{\sim}{k}.\underset{\sim}{R}$.
CONST	$Z_o/2\pi$
CONSTA	$Z_o \sin(l\pi\cos\theta_s)/6\pi\cos\theta_s$
CTHS2	$1 - \cos^2\theta_s$
CONBC	$Z_o/6\pi(1 - \cos^2\theta_s)$
INTERA	$\sin(\pi l\cos\theta_s)\cos(\pi l)$
INTERB	$\cos(\pi l\cos\theta_s)\sin(\pi l)$
CONSTB, CONSTC	Intermediate variable
FZRAR, FZRBR, FZRCR FZRAI, FZRBI, FZRCI	Real part of fields due to a, b and c Imaginary part of fields due to a, b and c
MAGTR, PHATR	Magnitude and phase of theta component of field
MAGPR, PHAPR	Magnitude and phase of phi component of field
COA, COB, COC	Contributions to farfield due to element, as if it was at the origin with a, b and c equal to 1.

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